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A finite element investigation of the relationship between bat taper geometry and bat durability

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Abstract

In a response to reverse the trend of a perceived increase in multi-piece failures (MPFs) of wood baseball bats in Major League baseball games, the Office of the Commissioner of Baseball implemented changes to the Wooden Baseball Bat Specifications (WBBS) in December 2008. These changes introduced bat-supplier regulations that outlined strict quantitative requirements for wood quality and instituted a third-party inspection of professional wooden baseball bats for the 2009 season. Additional changes to the WBBS for the 2010, 2011, and 2012 seasons targeted increasing the density of the wood used to make maple bats, thereby increasing the minimum breaking strength of the wood allowed for these bats. By the completion of the 2014 season, these changes had driven a 65% reduction in the rate of MPFs per game relative to the 2008 season. It is hypothesized that the rate of MPFs can be further reduced if regulations on the allowable geometries of the taper region for the bats used by MLB teams are implemented. To develop a fundamental understanding of the relationship among (1) the angle of the taper (2) the starting point of the taper along the length of the bat, and (3) wood density, a series of generic bat profiles that were subjected to bat/ball impacts was investigated using LS-DYNA. In this paper, the results of these bat/ball impact simulations are shared, and a summary of the various combinations of these geometric parameters on bat stress and strain is presented. The durability information gained from these generic bat profiles is then used to give guidance in understanding why certain bat profiles used in professional baseball have relatively high rates of MPFs while other profiles exhibit a relatively low rate of MPFs.

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Keywords: Baseball; Finite Elements; Imapct; Sports; Wood

1. Introduction

Since the beginning of Major League Baseball (MLB) over 140 years ago, wood bats have been breaking. Two broad categories of wood bat failures exist: single-piece failure (SPF) and multi-piece failure (MPF). A SPF is a failure where the bat stays intact or mainly in one piece. A MPF is a failure where the bat separates on failure into two or more significant-size pieces. In a response to reverse the trend of a perceived increase in MPFs of wood baseball bats in Major League games, the Office of the Commissioner of Baseball implemented changes to the Wooden Baseball Bat Specifications (WBBS) [1] in December 2008. These changes introduced bat-supplier regulations that outlined strict quantitative requirements for wood quality and instituted a third-party inspection of professional wood baseball bats. The December 2008 changes in the WBBS specifications resulted in an estimated 30% reduction in MPFs during the 2009 season relative to the 2008 season. Additional changes to the WBBS [2-5] from 2010-1012 have gradually increased the minimum allowable wood density of maple bats and have resulted in a 65% reduction in the MPFs relative to the 2008 season [6]. It is believed that the level of MPFs can be further reduced if the geometries of the bats are regulated so as to increase bat durability through a reduction in the stresses and strains experienced by the bat during bat/ball impacts. In this paper, parametric studies on the influence of the slope of the taper region (Figure 1) of the bat and the axial location of the taper are examined with respect to their influence on bat durability. Bat durability is defined here as the ability of a bat to experience a bat/ball impact without breaking the bat—the higher the relative bat/ball speed that a

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bat can tolerate without breaking, the greater the durability. The conclusion of the paper that bat durability is a function of geometry in combination with wood density.

2. Bat Profiles

There are four main regions of a bat: the knob, the handle, the taper, and the barrel. Each of these regions is denoted in Figure 1. The handle is the thinnest section of the bat, and as a consequence, it is very susceptible to breaking. However, players are very sensitive to any increase in the diameter of the handle, so any effort to increase this diameter is going to be met with resistance by the players. The next important section of the bat with respect to durability is the taper region of the bat. It is hypothesized that by invoking restrictions on the slope and diameter of the taper then bat durability can be further improved over what it is today.

Figure 1: Baseball bat with bat regions identified.

The specifications for Major League Baseball bat profiles require that the bat is made from a single piece of wood, no more than 6.63 cm (2.61 in.) in diameter and not more than 106.7 cm (42 in.) long [7]. These specifications allow for an infinite number of profiles to meet the personal preferences of a player. However, there is a relatively small number of profiles that are used by the majority of MLB players, and this small number of profiles spans the range of relatively good durability to relatively poor durability. For the current research, a select group of common professional profiles of varying perceived on-field durability will be examined.

Table 1: Profile Diameter and Volume Dimensions

Profile	**Handle** cm (in.)	**Taper** 30.5 cm (12 in.) from knob (in.)	**Taper** 38.1 cm (15 in.) from knob (in.)	**Barrel** cm (in.)	**Volume** cm^3 (in^3)
A	2.377 (0.936)	2.751 (1.083)	3.035 (1.195)	6.507 (2.562)	1394 (85.09)
B	2.408 (0.948)	2.573 (1.013)	2.883 (1.135)	6.241 (2.457)	1231 (75.10)
C	2.441 (0.961)	2.819 (1.110)	3.274 (1.289)	6.500(2.559)	1478 (90.19)

Table 1 highlights some of the geometrical differences among the three popular MLB bat profiles that have been selected for the current research. To blind the paper from using industry-specific profile designations, each profile designation is being designated by a single letter. Profile A is a moderate volume bat that is known to exhibit relatively average durability during gameplay and has the largest barrel of the three profiles. Profile B is a small volume bat that is known to be one of the most durable profiles available and has the smallest barrel of the three profiles. Profile C is known to exhibit the poorest durability of the three profiles and has the largest volume of the three profiles. Table 1 also includes the diameters at two locations along the taper region of each bat and the minimum diameter in the handle region.

The visual examination of the bat profiles was the motivation for a discussion about the role of the steepness of the slope in the taper region and its usefulness as an indicator of bat durability. The variation in the slope of the taper region was thought to be a possible explanation in regards to relating taper geometry to bat durability. A series of plots were produced to examine the slope gradient in various bat models. These plots examined the change in slope in 1.27-cm (0.5-in.) increments. Figure 2 is an example of one of those plots.

From histograms such as the one presented in Fig. 2, it was observed that the taper of bat profiles that exhibited good durability such as Profiles A and B had slopes that never exceeded 5^o whereas the taper of bat profiles that exhibited poor durability (e.g., Profile C) had slopes that exceeded 5^o. Thus, it was thought that the slope of the bat geometry might be a means of predicting relative durability. However, as this parameter was examined for histograms of a number of bat profiles that are used by MLB players and that span the range from good- to poor-durability bat models, it was realized that using the frequency of high-angle slope was not the sole explanation for relative bat durability.

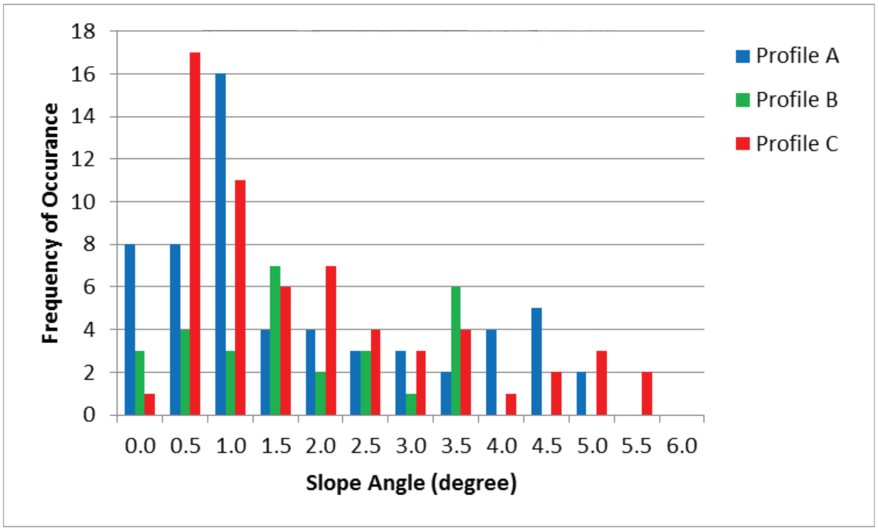

Figure 2: Plot showing the change frequency in slope angle in degrees for generic bat model.

3. Finite Element Modeling

To assist in understanding the relationship between the bat profile and bat durability, finite element modeling studies were conducted using LS-DYNA. These LS-DYNA studies were separated into two major approaches. The first approach investigated how changes in the slope of the taper region and in the starting position of the taper region influenced the stress state in a bat as a result of a bat/ball impact. Profile A was used as the basis for this parametric study. For these studies, all of the bats were of the same weight (0.88 Kg (31 oz.)) with material properties based on maple wood species at 10% moisture content. For this portion of the study, the wood density varied as a function of the overall volume of the bat so as to achieve the target bat weight. The second approach examined how the maximum strain level in the three professional profiles differed when the same wood density was used. Because the mechanical properties vary as a function of wood density, the use of the same density left the mechanical properties the same for this set of analyses. The results of the finite element studies can provide guidance for developing future standards for regulating the taper region of the bat in an effort to further reduce the frequency of MPF during MLB gameplay. The finite element models were constructed following the lessons learned and experiences gained from prior work conducted for investigating bat durability in LS-DYNA [8,9].

3.1. Investigation of taper starting position with constant taper angle

Three series of generic bat profiles were generated using HyperMesh and subsequently analyzed in LS-DYNA. These generic bats were variations of Profile A and configured to have a constant-slope (3^o, 4^o, or 5^o) in the taper region in combination with a prescribed axial position for the start of the taper (25.4 (10), 30.5 (12), and 35.6 cm (14 in.) from the base of the knob). The models generated for the 25.4 cm (10-in.) taper start can be seen in Figure 3. All bats were 86.4-cm (34-in.) long.

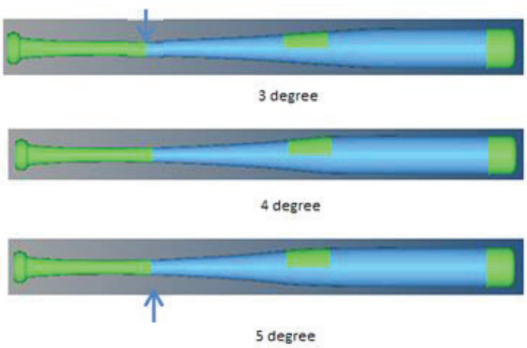

Figure 3: Finite element models of bats with 3^o, 4^o, and 5^o constant taper slopes and taper starting at 25.4 cm (10 in.) as measured from the base of the knob. These bats are a variation of Profile A – not to be confused with Profiles A, B and C.

All of the bats in the study were made of maple, and the same location along the length of the bat was used for all impact analyses. Maple was chosen as the wood to be used in all of the models because it is currently the most popular wood species used by MLB hitters. The maple wood properties used in the models were derived from the Wood Handbook [10] and a series of four-point bending dowel tests at the U.S.D.A. Forest Products Lab in Madison, WI. Bats were prescribed a density so as to model a 31 oz. bat, and the mechanical properties were scaled based on that density, e.g. the elastic modulus is linearly proportional to density. All simulations utilized an impact location of 35.6 cm (14 in.) as measured from the tip of the barrel with an impact velocity of 53.6 m/s (120 mph). These parameters were chosen because the 35.6-cm (14-in.) location lies within the taper region of the bat and 53.6 m/s (120 mph) represents 80% of maximum bat/ball impact at the 35.6-cm (14-in.) location assuming a swing speed of 35.7 m/s (80 mph) at the tip of the barrel and a pitch speed of 40.2 m/s (90 mph). This position on the bat corresponds to a typical inside pitch impact that is known to be detrimental to the bat. Inside pitches are responsible for roughly 2/3 of all MPFs seen during gameplay. For this study, no failure criteria were used in the models. After the simulations were run to completion, they were postprocessed in LS-PrePost to analyze the resulting maximum stress levels in the bats after impact.

Table 2: Summary of results for taper study models

Taper Slope (degrees)	Max stress (MPa) and taper start position		
	25.4 cm start	**30.5 cm start**	**35.6 cm start**
3	166.37	205.84	245.32
4	161.22	199.89	225.11
5	171.89	206.42	226.29

The results of the finite element simulations are summarized in Table 2. The results show that the maximum stresses were essentially the same for all combinations of taper angle at a given taper starting position. However, the maximum stress did vary significantly with respect to taper starting position. This result suggests that durability improves as the start of the taper moves toward the knob. Figure 4 shows the finite element models at the point of maximum stress for the 4^{o} taper slope starting at 25.4 (10), 30.5 (12), and 35.6 cm (14 in.) as measured from the base of the knob when impacted at 35.6 cm (14 in.) from the tip of the barrel. All fringe levels (maximum stress contours) in the illustrations are on the same scale for ease of comparison. Note how the shift in position of maximum stress follows the movement of the taper starting point as denoted by the white horizontal lines in Figure 4. The maximum stress for the 25.4 cm (10-in.) taper start is closer to the knob and has a lower maximum stress in comparison to the 35.6 cm (14-in.) taper start. This result is significant as the position of maximum stress indicates where failure would initiate in the bat.

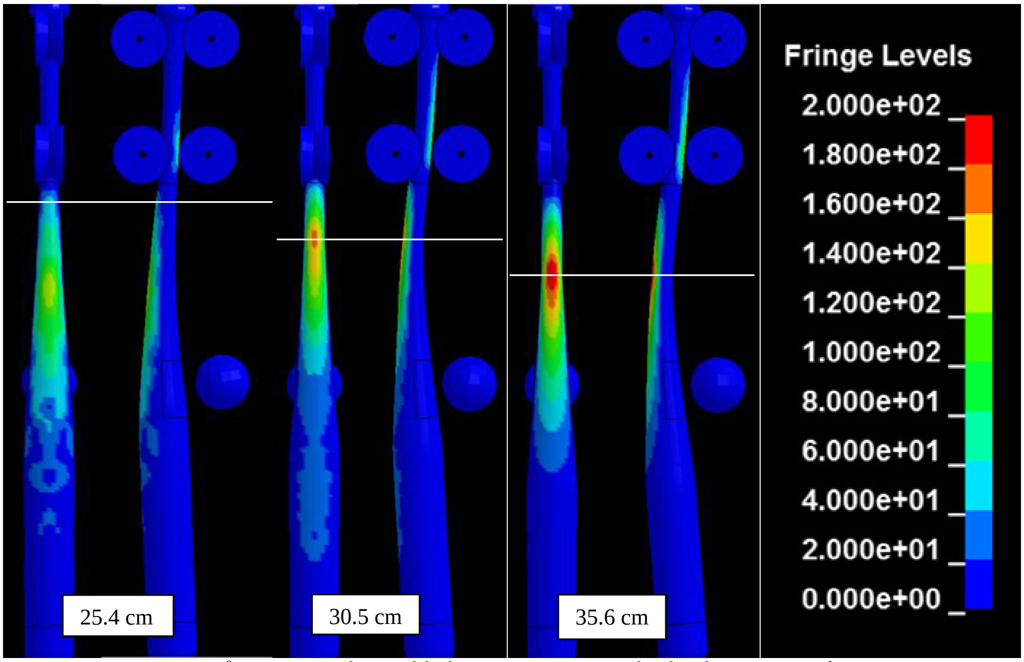

Figure 4: 4^{o} constant taper slope models showing stress contours, white line designates start of taper. (Dimension in the figure is the taper starting position as measured from the base of the knob)

3.2. Professional Profile Study

Finite element models of the three professional profiles that are cited in Table 1 were built and analysed. To limit the study to examine the effect of geometry on bat durability, all of the material properties were based on a wood density of 678.2 kg/m^3 (0.0245 lb/in^3), which is currently is the minimum-allowed maple wood density of bats for use in gameplay. Having held the density the same for all the profiles, it is assumed that the individual profile effect after impact can be analysed in isolation from the effect of wood density. Recall in the previous section all bat modelling varied the densities of the bat models so that the weight of the bat was 31oz.

The models were analysed for impacts at the 35.6 cm (14-in.) location to simulate the same inside pitch as was considered in the taper-study models. The impact velocities were set at 80% maximum velocity which is 53.6 m/s (120 mph) for an impact at the 35.6 cm (14-in.) location. No failure criteria were used in these models as the intent of this study was to examine the full stress/strain state in the bat profiles from the ball impact. Previous modelling studies focused on analysing the maximum stress in the bat after impact. However, it was decided that the maximum strain level in the bats might be a better parameter to indicate bat durability as previous bat modelling efforts by Ruggiero et al. [8,9] demonstrated good correlation to durability test results using a strain-to-failure criterion. The results of the modelling simulations after postprocessing are summarized in Table 3.

Table 3: Professional profiles modelled with same density and mechanical properties

Profile	Max Strain	Bat Weight [Kg (oz.)]	Volume [cm^3 (in^3)]	Wood Density [Kg/m^3 (lb/in^3)] for 0.88 Kg target weight	Wood Density of Bat Model [Kg/m^3 (lb/in^3)]
A	0.0226	0.967 (34.1)	1394 (85.09)	631.1 (0.0228)	678.2 (0.0245)
B	0.0233	0.850 (30.0)	1231 (75.10)	714.1 (0.0258)	678.2 (0.0245)
C	0.0177	1.01 (35.7)	1478 (90.19)	595.1 (0.0215)	678.2 (0.0245)

The results of the simulations were surprising. Profile B, which is the most durable of the three profiles, exhibited the largest strain at 0.0233. Profile C, which is the least durable of the three profiles, exhibited the smallest strain at 0.0177. Based on field-experience data, one would expect for Profile B to exhibit the lowest strain of the three profiles and for Profile C to have the highest. Because the density and mechanical properties are the same for all of the models in this portion of the study, the only reasonable explanation for the unexpected differences in maximum strain is the geometry of the profile.

Table 1 can help to understand the contradiction of the modelling results from what is seen on the field for the relative durability of these three profiles. In Table 1, it can be seen that the two diameters in the taper region for Profile C are much larger than these same diameters in Profiles A and B. Profile B has the smallest diameters for all the locations, which would indicate that the disparity in diameter size could explain the difference in the strain levels, i.e. the max strain decreased with increasing diameter. Essentially what this result shows is that if a profile is generated from the same piece of wood, the profile with larger diameters up through the taper region will exhibit superior durability. While this result is intuitively correct, i.e. bigger is better, and underwhelming, it brings to the forefront one of the true sources for the on-field relative durability of these three profiles, i.e. wood density.

For the current study, each of the A, B and C bat profiles was modelled using the same density. This same-density approach results in a wide span of overall bat weights as summarized in Table 3. For the case of each of these profiles being used for on-field play, the target weight would be 0.88 Kg (31 oz.). Table 3 lists the respective wood densities required to achieve the target weight for each of the profiles. As the volume of the bat increases from Profile B to A to C, the wood density decreases to meet the target weight. The on-field poor durability of Profile C implies that wood density may play a larger role in the relative durability of a bat than does the size of the taper region of the bat. Thus, there is trade-off between the geometry of the taper and the wood density for the roles that each plays with respect to bat durability.

4. Conclusions

The finite element studies provided insight into the profile geometry parameters that influence relative bat durability. For the range of taper angles considered (3^o to 5^o), no appreciable trend with respect to increasing or decreasing durability was observed. Therefore, at this time, regulating the high-angle sections of bat profiles does not look to be a viable approach to control relative bat durability. Significant durability change was observed for changing the taper start position – the closer to handle the taper begins the better the durability. Bat profiles with larger diameters closer to the handle exhibit lower maximum strain during impact than profiles with smaller diameters near the handle when considering the same wood properties. The density of wood used to manufacture baseball bats has an influence on the relative durability of the bat.

Acknowledgements

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